

Leptophobic Z' in Heterotic-String Derived Models

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Abstract

The CDF collaboration's recent observation of an excess of events in the Wjj channel may be attributed to a new Abelian vector boson with suppressed couplings to leptons. While D0 finds no evidence of an excess, the CDF data provide an opportunity to revisit an old result on leptophobic Z' in heterotic-string derived models. We re-examine the conditions for the existence of a leptophobic $U(1)$ symmetry, which arises from a combination of the $U(1)_{B-L}$ symmetry and the horizontal flavour symmetries, to form a universal $U(1)$ symmetry. While the conditions for the existence of a leptophobic combination are not generic, we show that the left-right symmetric free fermionic heterotic-string models also admit a leptophobic combination. In some cases the leptophobic $U(1)$ is augmented by the enhancement of the colour group, along the lines of models proposed by Foot and Hernandez.

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The discrepancy between the recent CDF [1] and D0 [2] results suggests considerable ambiguity as to whether there is an excess of Wjj events in the $M_{jj} \sim 140\text{GeV}$ region. Nevertheless, it is interesting to explore various theoretical scenarios that can account for such an excess. Indeed, various proposals appeared in the literature to explain the CDF results within and beyond the Standard Model [3, 4, 5]. One proposal amongst those attributes the discrepancy to a new Abelian vector boson in the appropriate mass range [4, 5]. However, since an enhancement in the dilepton channel is not observed, as well constraints arising from direct production at LEP II, Tevatron and LHC searches, the leptonic couplings of a putative Z' have to be suppressed.

Additional Abelian space-time vector bosons beyond those that mediate the $SU(3) \times SU(2) \times U(1)_Y$ subatomic interactions are abundant in extensions of the Standard Model [6]. Indeed, they arise in Grand Unified theories, based on $SO(10)$ and E_6 gauge extensions of the Standard Model gauge group, which are well motivated by the Standard Model matter states and charges. Similarly, Abelian extensions of the Standard Model are common in string theories. However, most of these extensions will produce extra bosons with unsuppressed coupling to leptons. It is therefore of interest to examine how a leptophobic Z' can arise [7, 5]. Obviously, one can simply gauge the baryon number $U(1)_B$, and this exercise has been undertaken, [8], and within type I string theories a gauged $U(1)_B$ may indeed arise. However, in Grand Unified theories, as well as in an heterotic-string theory that accommodates them, Abelian extensions of the Standard Model typically have unsuppressed couplings to leptons.

One exception to this generic expectation was the heterotic-string model of ref. [7]. The recent CDF data provide an opportune moment to re-examine how a leptophobic Z' can arise in heterotic-string models. In this respect the type I and heterotic-string cases imply different phenomenological signatures beyond the leptophobic Z' that will be instrumental in distinguishing between the two cases. While the heterotic-string maintains the Grand Unified embedding of the Standard Model states, the type I string does not. In particular, the heterotic-string can still preserve the embedding of the Standard Model matter states in spinorial 16 representations of $SO(10)$, which is well motivated by the Standard Model data. In the type I scenario the string scale is lowered to the TeV scale, which will be signalled by the emergence of Regge recurrences at parton collision energies $\sqrt{\hat{s}} \sim M_s \equiv \text{string scale}$. In the heterotic case the string scale is still at the Planck scale. The big desert between the weak and Planck scales is preserved, albeit with an unexpected oasis in between.

In this paper we therefore re-examine the ingredients that produced the leptophobic Z' model of ref. [7]. The main feature of this model is that the $U(1)_{B-L}$ gauge symmetry, which is embedded in $SO(10)$, plus a combination of the flavour $U(1)$ symmetry produces a family universal, leptophobic $U(1)$ symmetry. The additional $U(1)$ symmetries compensate for the lepton number in $U(1)_{B-L}$ and the resulting $U(1)$ therefore becomes a gauged baryon number. In the specific model of ref. [7]

the colour gauge symmetry is enhanced from $SU(3)_C \times U(1)_B$ to $SU(4)_C$, due to space-time vector bosons that arise from twisted sectors. We discuss how leptophobic $U(1)$ symmetries may arise in this class of superstring compactifications without enhancement of the gauge group. In particular, we show that the class of left-right symmetric models of ref. [9] reproduces the conditions that admits a leptophobic $U(1)$ combination without gauge enhancement.

The superstring models that we discuss are constructed in the free fermionic formulation [10]. In this formulation a model is constructed by choosing a consistent set of boundary condition basis vectors. The basis vectors, b_k , span a finite additive group $\Xi = \sum_k n_k b_k$ where $n_k = 0, \dots, N_{z_k} - 1$. The physical massless states in the Hilbert space of a given sector $\alpha \in \Xi$, are obtained by acting on the vacuum with bosonic and fermionic operators and by applying the generalised GSO projections. The $U(1)$ charges, $Q(f)$, with respect to the unbroken Cartan generators of the four dimensional gauge group, which are in one to one correspondence with the $U(1)$ currents $f^* f$ for each complex fermion f , are given by:

$$Q(f) = \frac{1}{2}\alpha(f) + F(f), \quad (1)$$

where $\alpha(f)$ is the boundary condition of the world-sheet fermion f in the sector α , and $F_\alpha(f)$ is a fermion number operator counting each mode of f once (and if f is complex, f^* minus once). For periodic fermions, $\alpha(f) = 1$, the vacuum is a spinor in order to represent the Clifford algebra of the corresponding zero modes. For each periodic complex fermion f there are two degenerate vacua, $|+\rangle, |-\rangle$, annihilated by the zero modes f_0 and f_0^* and with fermion numbers $F(f) = 0, -1$ respectively.

The realistic models in the free fermionic formulation are generated by a basis of boundary condition vectors for all world-sheet fermions [11, 12, 13, 14, 15, 9, 16]. The basis is constructed in two stages. The first stage consist of the NAHE set [17], which is a set of five boundary condition basis vectors, $\{\mathbf{1}, S, b_1, b_2, b_3\}$. The gauge group after the NAHE set is $SO(10) \times SO(6)^3 \times E_8$ with $N = 1$ space-time supersymmetry. The space-time vector bosons that generate the gauge group arise from the Neveu-Schwarz (NS) sector and from the sector $1 + b_1 + b_2 + b_3$. The Neveu-Schwarz sector produces the generators of $SO(10) \times SO(6)^3 \times SO(16)$. The sector $1 + b_1 + b_2 + b_3$ produces the spinorial 128 of $SO(16)$ and completes the hidden gauge group to E_8 . The vectors b_1, b_2 and b_3 produce 48 spinorial 16 of $SO(10)$, sixteen from each sector b_1, b_2 and b_3 . The vacuum of these sectors contains eight right-moving periodic fermions. Five of those periodic fermions produce the charges under the $SO(10)$ group, while the remaining three periodic fermions generate charges with respect to the flavour symmetries. Each of the sectors b_1, b_2 and b_3 is charged with respect to a different set of flavour quantum numbers, $SO(6)_{1,2,3}$.

The NAHE set divides the 44 right-moving and 20 left-moving real internal fermions in the following way: $\bar{\psi}^{1,\dots,5}$ are complex and produce the observable $SO(10)$ symmetry; $\bar{\phi}^{1,\dots,8}$ are complex and produce the hidden E_8 gauge group; $\{\bar{\eta}^1, \bar{y}^{3,\dots,6}\}$,

$\{\bar{\eta}^2, \bar{y}^{1,2}, \bar{\omega}^{5,6}\}$, $\{\bar{\eta}^3, \bar{\omega}^{1,\dots,4}\}$ give rise to the three horizontal $SO(6)$ symmetries. The left-moving $\{y, \omega\}$ states are divided into, $\{y^{3,\dots,6}\}$, $\{y^{1,2}, \omega^{5,6}\}$, $\{\omega^{1,\dots,4}\}$. The left-moving $\chi^{12}, \chi^{34}, \chi^{56}$ states carry the supersymmetry charges. Each sector b_1 , b_2 and b_3 carries periodic boundary conditions under $(\psi^\mu | \bar{\psi}^{1,\dots,5})$ and one of the three groups: $(\chi_{12}, \{y^{3,\dots,6} | \bar{y}^{3,\dots,6}\}, \bar{\eta}^1)$, $(\chi_{34}, \{y^{1,2}, \omega^{5,6} | \bar{y}^{1,2} \bar{\omega}^{5,6}\}, \bar{\eta}^2)$, $(\chi_{56}, \{\omega^{1,\dots,4} | \bar{\omega}^{1,\dots,4}\}, \bar{\eta}^3)$.

The division of the internal fermions is a reflection of the underlying $Z_2 \times Z_2$ orbifold compactification [18]. The Neveu–Schwarz sector corresponds to the untwisted sector and the sectors b_1 , b_2 and b_3 correspond to the three twisted sectors of the $Z_2 \times Z_2$ orbifold models. At this level there is a discrete S_3 permutation symmetry between the three sectors b_1 , b_2 and b_3 . This permutation symmetry arises due to the symmetry of the NAHE set and may be essential for the universality of the leptonophobic $U(1)$ symmetry. Due to the underlying $Z_2 \times Z_2$ orbifold compactification, each of the chiral generations from the sectors b_1 , b_2 and b_3 is charged with respect to a different set of flavour charges.

The second stage of the basis construction consists of adding three additional basis vectors to the NAHE set. Three additional vectors are needed to reduce the number of generations to three; one from each sector b_1 , b_2 and b_3 . One specific example is given in table 1. The choice of boundary conditions to the set of real internal fermions $\{y, \omega | \bar{y}, \bar{\omega}\}^{1,\dots,6}$ determines the low energy properties, like the number of generations, Higgs doublet–triplet splitting and Yukawa couplings [19].

The final gauge group in the free fermionic standard-like models arises as follows. The Neveu–Schwarz sector produces the generators of $SU(3)_C \times SU(2)_L \times U(1)_C \times U(1)_L \times U(1)_{1,2,3} \times U(1)_{4,5,6} \times \textit{hidden}$, where the *hidden* gauge group arises from the hidden E_8 gauge group of the heterotic-string in ten dimensions. The $SO(10)$ symmetry is broken to $SU(3)_C \times U(1)_C \times SU(2)_L \times U(1)_L^3$, where

$$\begin{aligned} U(1)_C &= \text{Tr} U(3)_C \Rightarrow Q_C = \sum_{i=1}^3 Q(\bar{\psi}^i), \\ U(1)_L &= \text{Tr} U(2)_L \Rightarrow Q_L = \sum_{i=4}^5 Q(\bar{\psi}^i). \end{aligned} \quad (2)$$

The flavour $SO(6)^3$ symmetries are broken to $U(1)^{3+n}$ with $(n = 0, \dots, 6)$. The first three, denoted by $U(1)_j$, arise from the world-sheet currents $\bar{\eta}^j \bar{\eta}^{j*}$ ($j = 1, 2, 3$). These three $U(1)$ symmetries are present in all the three generation free fermionic models which use the NAHE set. Additional horizontal $U(1)$ symmetries, denoted by $U(1)_j$ ($j = 4, 5, \dots$), arise by pairing two real fermions from the sets $\{\bar{y}^{3,\dots,6}\}$, $\{\bar{y}^{1,2}, \bar{\omega}^{5,6}\}$, and $\{\bar{\omega}^{1,\dots,4}\}$. The final observable gauge group depends on the number of such pairings. In the model of ref. [7] there are three such pairings, $\bar{y}^3 \bar{y}^6$, $\bar{y}^1 \bar{\omega}^5$ and $\bar{\omega}^2 \bar{\omega}^4$, which generate three additional $U(1)$ symmetries, denoted by $U(1)_{4,5,6}$. It is important to note that the existence of these three additional $U(1)$ currents is

³ $U(1)_C = \frac{3}{2}U(1)_{B-L}$ and $U(1)_L = 2U(1)_{T_{3R}}$.

correlated with a superstring doublet–triplet splitting mechanism [19]. Due to these extra $U(1)$ symmetries, the colour triplets from the NS sector are projected out of the spectrum by the GSO projections while the electroweak doublets remain in the light spectrum.

The key to understanding how the leptophobic $U(1)$ arises in the model of ref. [7] are the charges of the matter states from the sectors b_1 , b_2 and b_3 under the flavour $U(1)_j$ with $j = 4, 5, 6$. For example, the charges of the states from the sector b_1 are:

$$\begin{aligned} & (e_L^c + u_L^c)_{\frac{1}{2}, 0, 0, \frac{1}{2}, 0, 0} + \\ & (d_L^c + N_L^c)_{\frac{1}{2}, 0, 0, \frac{1}{2}, 0, 0} + \\ & (L)_{\frac{1}{2}, 0, 0, -\frac{1}{2}, 0, 0} + (Q)_{\frac{1}{2}, 0, 0, -\frac{1}{2}, 0, 0}, \end{aligned} \quad (3)$$

and similarly for the states from the sectors b_2 and b_3 . With these charge assignments, the quarks are charged with respect to the following combination

$$U(1)_B = \frac{1}{3}U_C - (U_{r_4} + U_{r_5} + U_{r_6}), \quad (4)$$

whereas the leptons are neutral with respect to it. Hence, this combination is a family universal, leptophobic $U(1)$ symmetry. In the model of ref. [7] additional space–time vector bosons arise from the sector $X = 1 + \alpha + 2\gamma$ in which $X_L \cdot X_L = 0$ and $X_R \times X_R = 8$. The additional vector bosons transform as triplets of $SU(3)_C$ and enhance it to $SU(4)_C$, where the $U(1)$ combination given by

$$U(1)_{B'} = U(1)_B - U_7 + U_9,$$

is the $U(1)$ generator of the enhanced $SU(4)$ symmetry. Here, U_7 and U_9 arise from the world–sheet complex fermions $\bar{\phi}^1$ and $\bar{\phi}^8$. The full massless spectrum and charges of this model were given in ref. [7]. In this model the $U(1)_{1,2,3}$ symmetries are anomalous with $\text{Tr}U_1 = 24$, $\text{Tr}U_2 = 24$ and $\text{Tr}U_3 = 24$. Hence, the family universal combination of these three $U(1)$ is anomalous, whereas the two family non–universal combinations are anomaly free. The $U(1)_{4,5,6,7,9}$, as well as $U(1)_{B-L}$, are, however, anomaly free. Hence, the leptophobic $U(1)$ combination is anomaly free and can remain, in principle, unbroken down to low scales.

The existence of a leptophobic, family universal and anomaly free $U(1)$ is highly non–trivial and not generic in phenomenological heterotic–string models. To demonstrate that this is indeed the case, we examine the model of [14]. The sectors $b_{1,2,3}$ produce the three chiral generations that are charged with respect to the same flavour symmetries, but differ from the corresponding charges in the model of ref. [7]. For example, the states from the sector b_1 carry the following charges:

$$\begin{aligned} & (e_L^c + u_L^c)_{\frac{1}{2}, 0, 0, \frac{1}{2}, 0, 0} + \\ & (d_L^c + N_L^c)_{\frac{1}{2}, 0, 0, -\frac{1}{2}, 0, 0} + \\ & (L)_{\frac{1}{2}, 0, 0, \frac{1}{2}, 0, 0} + (Q)_{\frac{1}{2}, 0, 0, -\frac{1}{2}, 0, 0}. \end{aligned} \quad (5)$$

We observe that e_L^c and L have like-sign charges under $U(1)_4$. Since they carry opposite sign charges under $U(1)_C$, $U(1)_4$ cannot be used to cancel the $B - L$ charge for both these states. Since they carry like-sign charges under $U(1)_1$, a leptophobic, family universal $U(1)$ cannot be made from these $U(1)$ symmetries. The model of ref. [14] preserves the cyclic permutation of the NAHE set. Hence, a similar charge assignment is obtained in the sectors b_2 and b_3 . In this model the flavour symmetries $U(1)_{4,5,6}$ are anomalous. Therefore, their combination with $U(1)_C$ is not anomaly free and must be broken.

As a second negative example, we consider the model of ref. [12]. In this model the states from the sector b_1 carry the following $U(1)$ charges

$$\begin{aligned} & (e_L^c + u_L^c)_{-\frac{1}{2},0,0,-\frac{1}{2},0,0} + \\ & (d_L^c + N_L^c)_{-\frac{1}{2},0,0,-\frac{1}{2},0,0} + \\ & (L)_{-\frac{1}{2},0,0,\frac{1}{2},0,0} + (Q)_{-\frac{1}{2},0,0,\frac{1}{2},0,0}. \end{aligned} \quad (6)$$

In this sector the combination given in eq. (4) is leptophobic. However, the states from the sector b_2 have charges

$$\begin{aligned} & (e_L^c + u_L^c)_{0,-\frac{1}{2},0,0,\frac{1}{2},0} + \\ & (d_L^c + N_L^c)_{0,-\frac{1}{2},0,0,-\frac{1}{2},0} + \\ & (L)_{0,\frac{1}{2},0,0,-\frac{1}{2},0} + (Q)_{0,\frac{1}{2},0,0,\frac{1}{2},0}, \end{aligned} \quad (7)$$

Hence, in this sector the combination (4) is not leptophobic and is not family universal. Furthermore, the flavour symmetries are anomalous in this model and, consequently, as is the combination given in eq. (4).

Is the existence of a leptophobic $U(1)$ combination therefore a peculiarity of the model of ref. ([7])? As seen from the charge assignments in eq. (3) the key is that the charges of the left- and right-handed fields differ in sign with respect to $U_{4,5,6}$ in the sectors b_1 , b_2 and b_3 , respectively. This model preserves the cyclic permutation symmetry of the NAHE set and therefore, the $U(1)$ combination in eq. (4), is family universal. Furthermore, $U(1)_{4,5,6}$ are anomaly free in the model of ref. [7] and therefore, their combination with $U(1)_{B-L}$ is also anomaly free. In this model the gauge symmetry is enhanced by space-time vector bosons arising from the twisted sectors. However, we can envision a more systematic classification, along the lines of ref. [22, 16], and that the extra bosons can be projected out from the spectrum in vacua that resemble the properties of this model. In such a case, the leptophobic $U(1)$ will arise without enhancement.

As seen from the other two examples provided by the models in refs. [14] and [12], the existence of a family universal, anomaly free leptophobic $U(1)$ combination in heterotic-string vacua is highly non-trivial. A class of models that reproduces the conditions for the existence of such a $U(1)$ combination are the left-right symmetric models of ref. [9]. However, in this case the $U(1)$ symmetries that are combined with

$U(1)_{B-L}$ are not the flavour $U(1)_{4,5,6}$, but rather the $U(1)_{1,2,3}$. This possibility is particular to the left–right symmetric heterotic–string models [9], and is not applicable in the other quasi–realistic free fermionic models, in which the $SO(10)$ symmetry is broken to the flipped $SU(5)$, $SO(6) \times SO(4)$ or $SU(3) \times SU(2) \times U(1)^2$ subgroups. The reason is that, in these cases, the charges of all the states from a given sector b_j are the same with respect to $U(1)_j$ with $j = 1, 2, 3$. This situation arises because the states from the sectors b_j in these models preserve the E_6 charge assignment under the decomposition $E_6 \rightarrow SO(10) \times U(1)$. A further consequence is that the $U(1)$ combination which arises from E_6 becomes anomalous in these models [21].

On the other hand, in the left–right symmetric models, the GSO projection that breaks the $SO(10)$ symmetry to $SU(3) \times U(1) \times SU(2)^2$ dictates that the $U(1)_{1,2,3}$ charges of the left–handed fields, Q_L and L_L , differs in sign from those of the right–handed fields, $Q_R \equiv u_L^c + d_L^c$ and $L_R \equiv e_L^c + N_L^c$. Their charges with respect to $U(1)_{4,5,6}$ may, or may not differ in sign. Hence, for example in the first model of ref. [9], we find for the sector b_1

$$\begin{aligned} & (u_L^c + d_L^c)_{\frac{1}{2}, 0, 0, \frac{1}{2}, 0, 0} + \\ & (e_L^c + N_L^c)_{\frac{1}{2}, 0, 0, -\frac{1}{2}, 0, 0} + \\ & (L)_{-\frac{1}{2}, 0, 0, \frac{1}{2}, 0, 0} + (Q)_{-\frac{1}{2}, 0, 0, -\frac{1}{2}, 0, 0}, \end{aligned} \quad (8)$$

with similar charges under $U(1)_{2,3}$ for the states from the sectors b_2 and b_3 , respectively. The $U(1)$ combination given by

$$U(1)_B = \frac{1}{3}U_C - U_1 - U_2 - U_3, \quad (9)$$

is family universal, anomaly free and leptophobic. In the left–right symmetric models, the $U(1)_{1,2,3}$ are anomaly free due to the specific symmetry breaking pattern and consequent charge assignments, whereas $U(1)_{4,5,6}$ may be anomalous or anomaly free in different models. The left–right symmetric free fermionic heterotic–string models therefore provide a second example that produces a potentially viable leptophobic $U(1)$ at low scales. In both cases, it is seen that the mechanism that yields a leptophobic $U(1)$ symmetry involves the existence of a combination of flavour $U(1)$ symmetries that nullifies the lepton number component of $U(1)_{B-L}$. The left–right symmetric models produce examples that are completely free of any gauge or gravitational anomalies. Specifically, all $U(1)$ symmetries in these models are anomaly free. Hence, any combination of the $U(1)$ symmetries, including the leptophobic combination, is anomaly free.

To guarantee that a $U(1)$ symmetry remains viable down to low scales, we must ensure that the spectrum remains anomaly free down to these scales. If we just consider the Standard Model states $U(1)_B$ has various mixed anomalies, which are compensated by additional states that arise in the string models. This additional spectrum is highly model dependent, but is constrained by the string charge assignments. The issue of how the $U(1)$ symmetry can remain viable down to low scales

is, therefore, model dependent and highly non-trivial. In type I string theories, this is solved by lowering the string scale down to the TeV scale. However, generically, one expects in this case, dangerous proton decay mediating operators to be generated (see, however, [20] that suggests otherwise). This scenario, in any case, has a distinct signature in the form of recurring Regge resonances, which will be confirmed or refuted in forthcoming LHC experiments. From the point of view of a bottom-up approach, gauging baryon number is possible by judiciously adding states with appropriate charges. However, the top-down approach relies on the states and charges that are compatible with the string charge assignments and other constraints. Therefore, the states that are contemplated in the bottom-up approach are not likely to exist in string constructions. Furthermore, string models typically produce exotic fractionally charged states that are severely constrained by experiments. String models in which the exotic states only appear in the massive spectrum do exist [16]. However, in these models the charge assignments are mundane. Recently, we have been able to construct effective field theories with an effective low scale $U(1)$ that suppresses proton decay mediating $U(1)$ [23]. However, this $U(1)$ is not leptophobic. All in all, an interesting possibility is that the enhanced non-Abelian symmetry in the model of ref. [7] is not superfluous, but required to maintain a viable leptophobic $U(1)$ down to the low scale. This scenario will then fall into the class of models considered in ref. [24], in which the colour group is enhanced. It has also been proposed [25] that this class of theories may explain the top forward-backward asymmetry, which is indicated by the CDF experiment [26]. While in the leptophobic model of ref. [7] the colour group is enhanced to $SU(4)$, enhancement to $SU(5)$ is also possible if $SU(3)_C$ combines with an hidden $SU(2)$ group factor.

In this paper we discussed how a leptophobic $U(1)$ symmetry may arise in heterotic-string derived models. The examples that we considered preserve the embedding of the Standard Model matter states in spinorial 16 representations of $SO(10)$. The leptophobic $U(1)$ arises from a combination of the $U(1)_{B-L}$ symmetry, which is embedded in $SO(10)$, and the horizontal flavour symmetries, which effectively cancels the lepton charge, resulting in a gauged baryon number. This may, or may not, be augmented by additional vector bosons that enhance the colour group. If forthcoming data provides further weight to the CDF claims, rather than to D0, the focus of model building will clearly shift in that direction.

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